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FINAL REPORT

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Production and Distribution

Research Center

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By

The School of Industrial and Systems Engineering

Georgia Institute of Technology

Atlanta, Georgia 30332

H.D. Ratliff

Principal Investigator

███████████

Telephone: (404)894-2300

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I. INTRODUCTION

It is increasingly apparent that some of the most difficult problems being addressed by both military and civilian enterprises relate to storing and moving materiel. This activity is essential to the support of all military employments and all civilian manufacturing and distribution functions. Materiel movement systems are expensive to build and operate. Also, they have a tremendous impact on other systems with which they interface. This is perhaps most apparent in military operations. Many military planners no longer ask "What is the best employment strategy?" but rather ask "What employment strategy can be best supported?". Hence, it is critical that there be a significant ongoing research program associated with optimally designing and operating systems for storing and moving materiel.

While problems in distribution and logistics have motivated much of the work in Industrial Engineering, Operations Research, and other areas of applied mathematics, relatively little of the research in these areas has been directed toward the understanding or solution of the kinds of problems actually faced by practitioners. The research effort has primarily concentrated on general optimization methodologies such as integer programming and very limited special abstractions such as the single machine scheduling problems. While the results of this research is interesting, it has not yet had a very significant impact on our ability to address the problems of greatest need. More importantly, recent results in problem complexity indicate that virtually all of the significant problems in distribution and logistics are in the class of problems which are not solvable in polynomial time.

Traditional research in mathematics is important since development of abstract mathematical models and concepts expands the tools we have at our command. However, if this abstract research is to have an impact on ultimately aiding planners and managers in addressing the pressing issues in distribution and logistics, a significant amount of mathematics research must also be focused on the follownig areas: (1) developing mathematical structures which enhance our understanding of the issues actually faced by practitioners in designing and operating distribution and logistics systems, (2) developing models and methodology which can be combined with the creative capabilities of human decision makers to facilitate the planning and design of distribution and logistics systems, (3) creating procedures and algorithms which, if not optimum, are predictable in the quality of the solutions generated for oprational distribution and logistics problems, and (4) using mathematical optimization structures as bases for design of distribution and logistics systems which can be effectively operated and controlled.

The value of basic research in these areas is demonstrated by the parallel effort underway with the Joint Deployment Agency (JDA). The previous research sponsored by ONR in the PDRC made design of the JDA system possible. The problems faced by JDA in planning deployments has in turn provided focus to our basic research effort. Because of the importance of the JDA effort in focusing much of our research, it is briefly discussed in Section III.

II. THE PRODUCTION/DISTRIBUTION RESEARCH CENTER

The Production/Distribution Research Center was established in July 1980 to accomplish three basic objectives: 1) to expand our knowledge of the fundamental problems associated with designing and operating production and distribution systems, (2) to develop new optimization methodologies which can be used to improve these processes, and (3) to provide a focal point for research in these areas.

The Center has become an important part of the developing rapport among private industry, governmental and military institutions, and the academic community. The School of Industrial and Systems Engineering (ISyE) at Georgia Tech houses the Center, whose primary originating funding source has been the Office of Naval Research (ONR). This funding permitted the establishment of the Center and supports its continuing development. The Center has also received research sponsorship from the Joint Deployment Agency, the Trasportation Systems Center, and the National Science Foundation. In addition, a number of private companies including Bethelem Steel, Coca Cola, Standard Oil of Ohio, and Martin Marietta have been involved in joint research with members of the Center.

The number of Faculty researchers within the Center varies between five and ten. The number of graduate students varies between five and fifteen.

Research in the Production and Distribution Research Center addresses basic questions associated with the configuration, operation, and assessment of manufacturing systems, storage systems, and delivery systems. The research is concentrated primarily on the use of

mathematical concepts and procedures to address problems related to movement and placement of people and materiel. `

System Configuration. Fundamental issues include: how to relate system objectives to design criteria; how to break the system into components; how to interface the components with each other; how to determine and assess the impact of acquisition strategy; how to size the system; how to select equipment; and how to lay out the components of the system.

System Operation. Fundamental issues include: how to position units to facilitate movement; how to group units for combined transportation; how to route vehicles; how to schedule resources; and how to develop system discipline.

System Assessment. Fundamental issues include: how to predict requirements; how to predict capability; how to measure performance in terms of requirements and capability; and how to structure, validate, maintain, and present information system data.

While the fundamental issues regarding placement and measurement of people and materiel and much of the developing mathematical methodology are very similar in manufacturing, storage, and delivery systems, the specific problems vary depending on context.

Since there is such a wide variety of problem contexts, the number of problems associated with the fundamental issues above is virtually limitless. A premise underlying the Center is that the commonality of issues will ultimately lead to unifying approaches for addressing these problems.

Production/distribution systems are usually complex and not amenable to exact global solution. Accordingly, we invoke the following basic philosophy of problem-solving: partition the system into more tractable

but natural subproblems, develop solution techniques for the subproblems, and then develop methods of integrating subproblem solutions so that system-wide performance is enhanced. Frequently, the subproblems correspond to physical components of the system. For example, to increase the throughput of a warehouse, we are lead to consider subproblems related to increasing the throughput of individual components such as a carousel conveyor. Then we must consider how to increase the throughput of a system of carousel conveyors, and, beyond this, how to integrate systems of carousel conveyors into the overall functioning of the warehouse. Thus, as in this example, we build from effective control of component subsystems to effective control of the total system.

Some of the smaller problems are so tractable as to succumb to optimization techniques, which we develop as appropriate. Most problems, however, resist such solution. For these more difficult problems we invoke one of two general approaches, depending on the nature of the problem environment. Operating decisions tend to be made frequently and allow little time for reflection. For such problems we develop heuristics that require minimal computational effort, yet provide solutions of acceptable quality. This requires consideration of complexity, probabilistic analysis, and worst case analysis of decision techniques.

Design decisions tend to be made infrequently but have long term, expensive implications for system operation. Thus, in-depth analyses can be justified. For these problems the concept of "human aided optimization" seems the most promising. This concept involves underlying mathematical models (e.g., optimization, queueing, simulation), a computer graphics interface and a human decision maker. The human guides

the process, utilizing primarily graphical information and makes the ultimate decisions. The models suggest and help evaluate alternatives based on input from the human decision maker. The research effort includes developing new models and solution techniques, analyzing the proper role of the human decision maker, and determining graphical interfaces which can provide the human with the necessary insight to guide the process. It also includes the use of mathematical optimization concepts to provide a structure for teams of designers working in parallel and to provide design structures which provide the basis for logistics and distribution systems which can be effectively operated and controlled.

A logistics design laboratory has been constructed within the PDRC to test design concepts, particularly those related to team design. It has a dedicated IBM 4341 computer supported by six IBM 3179 terminals, six IBM PC/XTs, eight wall mounted chromatics CX-1300 color graphics displays, and a large screen projection system.

The IBM 4341 allows testing of very large optimization models and algorithms. The wall mounted high resolution color graphics units and large screen projection allows display of a graphical information to a team of designers. This allows development and testing of both the mathematics and the human interface for interactive optimization based design of distribution and logistics systems.

III. THE JOINT DEPLOYMENT AGENCY (JDA) EFFORT

PDRC faculty are in the fourth year of an ongoing effort for the Joint Deployment Agency (JDA) to develop operational models for deployment planning in a crisis action environment. The problems involve planning for the effective utilization of lift assets (planes, ships, trucks, trains, etc.) in the delivery of movement requirements (men, materiel, fuel, resupply, ammunition, etc.) to a specified objective area in support of a military crisis action.

The PDRC has been asked to examine the deployment planning problem, develop appropriate models and algorithms, design implementation strategies, and suggest concepts of operation involving interactive human control in a decision support planning environment. An initial report, PDRC 82-22, outlined the problem and suggested a framework for model/algorithmic development. PDRC Report 83-06 concentrated on the models and concepts for the initial phase (closure planning) of crisis action deployment planning. PDRC Report 84-09 provides an overall system description for the crisis action system.

One of the fundamental optimization models we have developed for deployment planning has hundreds of millions of variables and a million or more constraints. It can be decomposed into a generalized flow problem and a flow with side constraints problem. For large deployments where a great deal of detail is desired, the size of these problems is beyond current computing capability.

This has motivated a serious basic research effort into aggregation and decomposition as means for increasing the size of the problem which can be solved in the time allowed. Some of the results of this research is reported in PDRC Report 84-10. Work will continue in this effort.

In addition, JDA and Georgia Tech have jointly funded the Logistics Laboratory discussed earlier which is based at Georgia Tech. It provides a tremendous opportunity for further research into marrying basic mathematical optimization with human judgement to solve complex military problems.

The JDA research effort, while itself focusing on immediate gains, has spawned companion research within the PDRC on long term development of basic methodology in solution of a wide range of delivery/deployment problems as well as more general optimization models and methodology.

IV. SUMMARY OF ACCOMPLISHMENTS

We feel that the ongoing basic research program within the Production/Distribution Research Center will continue to have a very significant impact on the role of mathematics in addressing problems related to materiel movement and storage. The research is developing fundmentally new mathematical concepts, such as spacefilling curves, as well as innovative methodologies such as interactive optimization for imbedding mathematics into fundamental design processes. In addition the research is addressing the fundamental issues in scheduling, storage configuration, routing, and layout which need to be resolved in order to address the complex real-world material movement problems faced by the U.S. Military. The effort with the Joint Deployment Agency is an indication of the potential for more closely integrating basic research in mathematics with actual military problems.

During 1981-85 there have been 23 research reports published relating to results developed within the PDRC under Offce of Naval Research sponsorship. These reports are listed in Appendix A. Many of these reports are now beginning to appear in refereed publications. There have been 13 refereed papers (Appendix B) published during 1983-85. There are an additional 9 papers (Appendix C) currently under review for journal publication and a substantial number being prepared for publications. There have also been numerous invited presentation (Appendix D) of this work at national and international meetings.

We feel that our research effort is well focused and is providing significant basic research results. We propose to continue the current research direction.

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APPENDICES

APPENDIX A
PDRC RESEARCH REPORTS 1981-85
Sponsored by Office of Naval Research

81-01 Engineering/Production Integration Workshop
       Leon F. McGinnis

81-02 Minimizing the Makespan in a Stochastic Flowship
       Michael L. Pinedo

81-03 On the Optimal Order of Stations in Tandem Queues
       Michael L. Pinedo

81-04 A Note on Approximate Solutions to the Travelling Salesman Problem
       John J. Bartholdi, III

81-05 Minimizing Expected Makespan in Stochastic Open Shops
       Michael L. Pinedo and Sheldon Ross

81-06 Periodic Scheduling to Minimize Maximum Delay
       John J. bartholdi and Arnon S. Rosenthal

81-07 Comparison Between Deterministic and Stochastic Scheduling
       Problems with Release Dates and Due Dates
       Michael L. Pinedo

81-08 A Comparison Between lRandem Queues with Dependent and Independent
       Service Times
       Michael Pinedo and Ronald W. Wolff

81-09 Storage System Optimization
       Jessica O. Maston and John W. White

81-10 Order-Picking in a Rectangular Warehouse: A Solvable Case of the
       Travelling Salesman Problem
       H. Donald Ratliff and Arnon S. Rosenthal

81-11 On the Computational Complexity of Stochastic Scheduling Problems
       Michael Pinedo

81-12 Stochastic Shop Scheduling: A Survey
       Michael L. Pinedo and Linus Schrage

81-13 A Branch and Bound Based Heuristic for Solving the Quadratic
       Assignment Problem
       M.s. Bazaraa and O. Kirca

81-14 Scheduling Exponential Jobs on Two Machines with Resource
       Constraints
       Michael L. Pinedo

81-15 Some Equivalent Objectives for Dynamic Network Flow Problems
       John J. Jarvis and H. Donald Ratliff

82-19 Assigning Materials to Storage Locations in Automated Storage and Retrieval Systems: An Interactuve Approach
J. A. White and Shea

82-20 Service Level Considerations
F.H. Cullen, J. J. Jarvis, H.D. Ratliff and E. Frautchi

82-21 Aggregate Production Planning Models for Bethlehem Steel
J. J. Jarvis, H.D. Ratliff and D.Y.Su.

82-22 Systems for Closure Optimization Planning and Evaluation (SCOPE)
J.J. Jarvis and H. D. Ratliff

83-01 A Minimal Technology Routing Systems
J. J. Bartholdi, III, L. K. Platzman, R. L. Collins and W.H. Warden, III

83-02 Spacefilling Curves and Routing Problems in the Plane
J. J. Bartholdi, III and L. K. Platzman

83-03 A Fast Heuristic Based on Spacefilling Curves for Minimum-Weight Matching in the Plane
John J. Bartholdi, III and Loren K. Platzman

83-04 How to Implement a Simple Routing System
John J. Bartholdi, III, L. K. Platzman, R. L. Collins and W. H. Warden, III

83-05 Decomposition Method for Optimal Lot Sizing in Acyclic Production Systems
L. F. McGinnis

83-06 System for Closure Optimization Planning and Evaluation (SCOPE)
John J. Jarvis and H. Donald Ratliff

83-07 Lot Sizinig in Acyclic Production Systems: Some Empirical Results
V. V. Rao and L. F. McGinnis

83-08 Shared Versus Dedicated Storage Policies
Marc Goetschalckx and H. Donald Ratliff

83-09 Facility Layout
Leon F. McGinnis

83-10 A Heuristic for the Pallet Movement Problem in Naval Supply
John J. Jarvis and Omer Kirca

83-11 Order Picking in a Single Aisle
M. Goetschalckx and H.D. Ratliff

84-01 Network Flow Algorithms: Systems for Closure Opotimization Planning and Evaluation (SCOPE)
John J. Jarvis, H.D. Ratliff, Michael Trick

84-04 Network Flow Models for Energy Allocation Problems
John J. Jarvis and Michael Trick

84-06 On Sequencing Retrievals in an Automated Storage/Retrieval System
L. F. McGinnis, J. Han, S. Shieh, J. A. White

84-07 Modeling Block Stacking Storage Systems
Jessica O. Matson and John A. White

84-08 Heuristics Based on Spacefilling Curves for Combinatorial Problems
in the Plane
John J. Bartholdi, III and Loren K. Platzman

84-09 System Description: System for Closure Optimization Planning and
Evaluation (SCOPE)

84-10 Solving Transportation Problems via Aggregation
Richard W. Taylor and C.M. Shetty

84-11 Relative Performance of Micro and Mainframe Computers
Marc Goetschalckx and Yavuz Bozer

84-12 Pick-up and Delivery Problem: Models and Single Vehicle Exact
Procedures
John J. Jarvis and Omer Kirca

84-13 A Simple and Efficient Algorithm to Compute Tail Probabilities
from Transforms
L. K. Platzman, J.C.1 Ammons and J. J. Bartholdi, III

84-14 More on the Evolution of Coopoeration
John J. Bartholdi, C. Allen Butler and Michael A. Trick

84-15 Retrieval Strategies for a Carousel Conveyor
John J. Bartholdi, III and Loren K. Platzman

85-01 A Decomposition Procedure for Convex Quadratic Programs
C. M. Shetty and Mohaammed Ben Daya

85-02 On the Step Size in Karmarkar's Algorithm
C.M. Shetty and Den Daya

85-03 Sensitivity Feedback (Bender's Decomposition): Systemf for
Closure Optimization Planning and Evaluation (SCOPE)
J.J. Jarvis, H.D. LRatliff and D. Eisenstein

85-04 Network Aggregation Concepts
A.V. Iyer, J.J. Jarvis and H.D. Ratliff

Appendix B

ONR Suppled Papers Published in Refereed Journals During 1983-85

Bartholdi, J.J., L.K. Platzman, R.L. Collings, and W.H. Warden (1983). "A Minimal Technology Routing System for Meals-on Wheels," cover article of Interfaces 13(3), pp. 1-8.

Bartholdi, J.J. and L.K. Platzman (1983). "A Fast Heuristic Based on Spacefilling Curves for Minimum-Weight Matching in the Plane," to appear in Information Processing Letters.

Francis, R.L., L.F. McGinnis and J.A. White, (1983). "Locational Analysis," European Journal of Operations Research, Vol. 12, pp. 220-252.

Pinedo, M. "Stochastic Scheduling with Release Dates and Due Dates," (May-June 1983), Operations Research Vol. 31, No. 3, pp. 559-572.

Pinedo, M. "Minimizing Expected Makespan in Stochastic Open Shops," (December 1982), Adv. Appl. Prob. Vol. 14, pp. 898-911.

Rao, V.V. and L.M. McGinnis, "Optimal Lot Sizing in Acyclic Multiperiod Production Systems," (1983). IIE Transactions Vol. 15, No. 1, pp. 54-62.

Ratliff, H.D. and A. Rosenthal, (May-June 1983). "Order Picking in a Rectangular Warehouse: A Solvable Case of the Travelling Salesman Problem," Operations Research Vol. 31, No. 3, pp. 507-521.

Pinedo, M. "A Note of the Flow Time and The Number of Tardy Jobs in Stochastic Open Shops," European Journal of Operational Research 18(1984) pp. 81-85.

Pinedo, M. "Scheduling Jobs with Exponentially Distributed Processing Times on Two Machines with Resource Constraints," Management Science, Vol. 30, No. 7, July 1984.

Pinedo, M. "Inequalities and Bounds in Stochastic Shop Scheduling," SIAM J. Appl. Math., Vol. 44, No. 4, August 1984.

McGinnis, L.F., J. Hon, S. Shieh, and J.A. White, "On Sequencing Retrievals in an Automated Storage/Retrieval System," IIE Transactions, to appear 1985.

Bartholdi, J.J., A. Butler,and M. Trick (1985). "More on the Evolution of Cooperation," J. Conflict Resolution, to appear 1985.

Bartholdi, J.J., "Operations Research in China," Interfaces, to appear 1985.

Appendix C

ONR supported Papers Currently in Refereeing

"Solving Transportation Problems via Aggregation," under review by Computers and Operations Research.

"Solving Large Scale Linear Programs by Aggregation," under review by Computers and Operations Research.

"Shared Versus Dedicated Storage Policies," under review by Management Science.

"Order Picking in a Single Aisle," under review by IIE Transactions.

"Matching Based Interactive Facility Layout," order review by IIE Transactions.

"A Simple and Efficient Algorithm to Compute Tail Probabilities from Transforms," under review by Operations Research.

"Retrieval Strategies for a Carousel Conveyor," under review by IIE Transactions.

"Heuristics Based on Spacefilling Curves for Combinatorial Problems in the Plane," under review by Management Science.

"Spacefilling Curves and the Planar Travelling Salesman Problem," under review by Journal of the Association for Computing Machinery.

Appendix D

Invited Presentations on ONR Sponsored Research Given in 1983-85

Bartholdi, J. "Network Substructure is Hard to Find," ORSA/TIMS Joint National Meeting, Chicago, April 1983.

Bartholdi, J. and L. Platzman. "A Heuristic Routing Method Based on Spacefilling Curves," ORSA/TIMS Joint National Meeting, Chicago, April 1983.

Bartholdi, J. and L. Platzman. "Bin Numbering for Efficient Warehouse Retrieval," ORSA/TIMS Joint National Meeting, Orlando, November 1983.

Bartholdi, J. and L. Platzman. "A Minimal Technology Routing System Based on Spacefilling Curves," presented at
- The University of Florida, Department of Industrial and Systems Engineering, Seminar, February 1983,
- Massachusetts Institute of Technology, Graduate Seminar in Operations Research, March 1983, and
- Fermi National Accelerator Laboratory, Colloquium, October 1983.

Jarvis, J.J. "Interactive Routing," Second International Dairy Federation Workshop on Computerized Bulk Milk Collection Systems, Toronto, Ontario, CANADA, September 1983.

Van Landeghem, H. and H.D. Ratliff. "A Procedence for Interactive Routing and Time Scheduling," TIMS/ORSA Joint National Meeting, April 1983.

Ratliff, H.D. "Interactive Layout Methodology," Advanced Institute for Material Handling Teachers, Auburn University, June 1983.

Ratliff, H.D. "Interactive Routing," Symposium on Vehicle Routing, Cornell University, July 1983.

Ratliff, H.D. "Interactive Scheduling and Routing," Symposium on Scheduling and Routing, Columbia University, October 1983.

McGinnis, L.F. and R. Dickson. "Storage Configuration," ORSA/TIMS Joint National Meeting, Orlando, November 1983.

McGinnis, L.F. and J.C. Ammons. "Expected Deficit Reliability Constraint for Mixed Integer Programming Models of Long Range Generation Expansion Planning in Electric Utilities," ORSA/TIMS Joint National Meeting, Orlando, November 1983.

McGinnis, L.F. and A. Rizo-Patron. "Throughput of Analysis of Advanced AS/R Systems," ORSA/TIMS Joint National Meeting, San Francisco, May 1984.

Bartholdi, J. and L. Platzman. "Spacefilling Curves Help Solve Combinatorial Problems," ORSA/TIMS Joint National Meeting, San Francisco, May 1984.

Bartholdi, J., L. Platzman, and J. Ammons. "Why are Tail Probabilities So Hard to Compute and What Can We Do About It?" ORSA/TIMS Joint National Meeting, San Francisco, May 1984.

Bartholdi, J. and L. Platzman. "Distribution Systems Trends," Advanced Technologies Exposition, Material Handling Institute Show and Forum, Houston, April 1984.

Bartholdi, J. "The Difficulty of Forecasting the Future of Non-Linear Dynamical Systems," Symposium on Chaos, Georgia Institute of Technology, July 1984.

Bartholdi, J. and L. Platzman. "Design and Evaluation of Heuristic Algorithms," ORSA/TIMS Joint National Meeting, Dallas, November 1984.

McGinnis, L.F. "Crane Distribution for a Tote Storage/Retrieval System (TS/RS)," ORSA/TIMS Joint National Meeting, Dallas, November 1984.

Jarvis, J.J. and H.D. Ratliff. "Interactive Optimization," ORSA/TIMS Joint National Meeting, Dallas, November 1984.

Jarvis, J.J. andd H.D. Ratliff. "Systems for Closure Optimization Planning and Evaluation (SCOPE): A Framework for Crisis Action Deployment Planning," ORSA/TIMS Joint National Meeting, Dallas, November 1984.

Shetty, C.M. "A Decomposition Procedure for Quadratic Progarms," ORSA/TIMS Joint National Meeting, Atlanta, November 1985.

Shetty, C.M. "Aggregation in Mathematical Programming," IEEE/SMC Conference, Tucson, November 1985.

Jarvis, J.J. and H.D. Ratliff. "Interactive Optimization" ORSA/TIMS Joint National Meeting, Dallas, November 1985.

Martin-Vega, L.A. and H.D. Ratliff "Operational Rules for a Class of Kitting Problems", ORSA/TIMS Joint National Meeting, Atlanta, November 1985.

Goetschalckx, Marc and H.D. Ratliff "Order Picking In An Aisle", ORSA/TIMS Joint National Meeting, Atlanta, November 1985.

Jarvis, John J., H.D. Ratliff and Trick, Michael A. "Generalized Network Implementations On Microcomputers", ORSA/TIMS Joint National Meeting, Atlanta, November 1985

Jarvis, John J., Nulty, William G. and Ratliff, H. D. "Scope Prototype Deployment Planning Model", ORSA/TIMS Joint National Meeting, Atlanta, November 1985